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Another step towards a no-lose theorem for NMSSM Higgs discovery at the LHC

S. Moretti, S. Munir and P. Poulose

High Energy Physics Group, School of Physics & Astronomy, University of Southampton, Southampton, SO17 1BJ, UK

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Abstract

We show how the LHC potential to detect a rather light CP-even Higgs boson of the NMSSM, H_1 or H_2, decaying into CP-odd Higgs states, A_1A_1, can be improved if Higgs-strahlung off W bosons and (more marginally) off top-antitop pairs are employed alongside vector boson fusion as production modes. Our results should help extracting at least one Higgs boson signal over the NMSSM parameter space.

The Minimal Supersymmetric Standard Model (MSSM) is affected by the so-called 'μ-problem'. Its Superpotential contains a dimensionful parameter, μ, that, upon Electro-Weak Symmetry Breaking (EWSB), provides a contribution to the masses of both Higgs bosons and Higgsino fermions. Furthermore, the associated soft Supersymmetry (SUSY) breaking term mixes the two Higgs doublets. Now, the presence of μ in the Superpotential before EWSB indicates that its natural value would be either 0 or the Planck mass M_P. On the one hand, $\mu = 0$ would mean that no mixing is actually generated between Higgs doublets at any scale and the minimum of the Higgs potential occurs for $< H_d >= 0$, so that one would have in turn massless down-type fermions and leptons after SU(2) symmetry breaking. On the other hand, $\mu \approx M_P$ would reintroduce a 'fine-tuning problem' in the MSSM since the Higgs scalars would acquire a huge contribution $\sim \mu^2$ to their squared masses (thus spoiling the effects of SUSY, which effectively removes otherwise quadratically divergent contributions to the Higgs mass from SM particles). Therefore, the values of this (arbitrary) parameter μ are phenomenologically constrained to be close to $M_{\rm SUSY}$ or M_W.

The most elegant solution to the μ-problem is to introduce a new singlet scalar field S into the theory and replace the μ-term in the MSSM Superpotential by an interaction term[1]

[1]Hereafter, hatted variables describe Superfields while un-hatted ones stand for the corresponding scalar components.

$\sim \hat{S}\hat{H}_u\hat{H}_d$. At the same time, also the soft term $B\mu H_u H_d$ is replaced by the dimension-4 term $\sim A_\lambda S H_u H_d$. When the extra scalar field S acquires a Vacuum Expectation Value (VEV), an effective μ term, naturally of the EW scale, is generated automatically. This idea has been implemented in the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [1], described by the Superpotential

$$W_{\rm NMSSM} = \hat{Q}\hat{H}_u\mathbf{h_u}\hat{U}^C + \hat{H}_d\hat{Q}\mathbf{h_d}\hat{D}^C + \hat{H}_d\hat{L}\mathbf{h_e}\hat{E}^C + \lambda\hat{S}(\hat{H}_u\hat{H}_d) + \frac{1}{3}\kappa\hat{S}^3, \qquad (1)$$

where $\hat{S}$ is an extra Higgs iso-singlet Superfield, λ and κ are dimensionless couplings and the last (Z_3 invariant) term is required to explicitly break the dangerous Peccei-Quinn (PQ) U(1) symmetry [2][2]. (See Ref. [4] for NMSSM Higgs sector phenomenology with an exact or slightly broken PQ symmetry.) However, due to its Z_3 symmetry, the NMSSM has a domain wall problem, as discussed in the last few references in [5]. This is to be solved by additional terms that break Z_3 explicitely. Although the latter can generate dangerous tadpole diagrams, as discussed in the first few references in [5], scenarios that solve both problems simultaneously are proposed in [6]. (Alternative formulations to the NMSSM – known as the Minimal Non-minimal Supersymmetric Standard Model (MNSSM) and new Minimally-extended Supersymmetric Standard Model or nearly-Minimal Supersymmetric Standard Model (nMSSM) – exist [7].) Another positive feature of all these non-minimal SUSY models is that they predict the existence of a (quasi-)stable singlet-type neutralino (the singlino) that could be responsible for the Dark Matter (DM) of the universe, albeit this occurs only in limited regions of parameter space [8]. Finally, in these extended SUSY models, the singlet Superfield $\hat{S}$ has no SM gauge group charge (so that MSSM gauge coupling unification is preserved) and one can comfortably explain the baryon asymmetry of the Universe by means of a strong first order EW phase transition [9] (unlike the MSSM, which requires a light top squark and Higgs boson barely compatible with experimental bounds [10]).

Clearly, in eq. (1), upon EWSB, a VEV will be generated for the real scalar component of $\hat{S}$ (the singlet Higgs field), $< S >$, alongside those of the two doublets $< H_u >$ and $< H_d >$ (related by the parameter $\tan\beta =< H_u > / < H_d >$). In the absence of fine-tuning, one should expect these three VEVs to be of the order of $M_{\rm SUSY}$ or M_W, so that now one has an 'effective μ-parameter', $\mu_{\rm eff} = \lambda < S >$, of the required size, thus effectively solving the μ-problem. In the end, in the NMSSM, the soft SUSY-breaking Higgs sector is described by the Lagrangian contribution

$$V_{\rm NMSSM} = m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right), \qquad (2)$$

with A_λ and A_κ dimensionful parameters of $\mathcal{O}(M_{\rm SUSY})$.

As a result of the introduction of an extra complex singlet scalar field, which only couples to the two MSSM-type Higgs doublets, the Higgs sector of the NMSSM comprises of a total of seven mass eigenstates: a charged pair $H^\pm$, three CP-even Higgses $H_{1,2,3}$ ($M_{H_1} < M_{H_2} <$

[2]One could also gauge the $\mathrm{U(1)_{PQ}}$ group, so that the Z_3 symmetry is embedded in the local gauge symmetry [3].

M_{H_3}) and two CP-odd Higgses $A_{1,2}$ ($M_{A_1} < M_{A_2}$). Consequently, Higgs phenomenology in the NMSSM may plausibly be different from that of the MSSM.

In view of the upcoming CERN Large Hadron Collider (LHC), quite some work has been dedicated to probing the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [1] Higgs sector over recent years. Primarily, there have been attempts to extend the so-called 'no-lose theorem' of the MSSM [11] to the case of the NMSSM [12, 13][3]. From this perspective, it was realised that at least one NMSSM Higgs boson should remain observable at the LHC over the NMSSM parameter space that does not allow any Higgs-to-Higgs decay. However, when the only light non-singlet (and, therefore, potentially visible) CP-even Higgs boson, H_1 or H_2, decays mainly to two very light CP-odd Higgs bosons, A_1A_1, one may not have a Higgs signal of statistical significance at the LHC.

From the preliminary studies in Ref. [13] though, it appeared that using the $qq \to qqW^+W^-, qqZZ \to qqH_{1,2} \to qqA_1A_1$ detection mode, i.e., via Vector Boson Fusion (VBF), may lead to the possibility of establishing a no-lose theorem in the NMSSM, particularly if the lightest CP-odd Higgs mass is such that there can happen abundant $A_1A_1 \to b\bar{b}\tau^+\tau^-$ decays, with both τ-leptons being detected via their e, μ leptonic decays[4]. At high luminosity, this signal may be detectable at the LHC as a bump in the tail of a rapidly falling mass distribution. However, this procedure relies on the background shape to be accurately predictable. These analyses were based on Monte Carlo (MC) event generation (chiefly, via the SUSY routines of the `HERWIG` v6.4 code [17]) and a toy detector simulation (`GETJET`, based on UA1 software). Further analyses based on `PYTHIA` v6.2 [18] and a more proper ATLAS detector simulation (`ATLFAST`) [19] found that the original selection procedures may need improvement in order to extract a signal [20].

While the jury is still out on this particular analysis, we would like here to advertise the possibilities offered by exploiting Higgs-strahlung (HS) off gauge bosons ($q\bar{q}' \to W^{\pm *} \to W^\pm H_{1,2}$, with a subleading component from $q\bar{q} \to Z^{0*} \to Z^0 H_{1,2}$) and, more marginally, off heavy quark pairs (chiefly top quarks, $q\bar{q}, gg \to t\bar{t}H$, because of the small $\tan\beta$ values involved in the scenarios outlined in [13]) as the underlying Higgs production modes, in place of or – better – alongside VBF. In fact, for the $H_{1,2}$ masses of relevance to the above analyses, say, 50 to 120 GeV, Higgs-strahlung gives cross sections comparable to VBF, if not larger for smaller $M_{H_{1,2}}$ values. However, we will not be performing here a detector analysis, including parton shower and hadronisation effects, as in [13, 19]. Rather, in this brief report, we will limit ourselves to proving that, after enforcing standard LHC triggers (at partonic level) on W decays in Higgs-strahlung and on forward/backward jets in VBF, there are regions of NMSSM parameter space were the yield of the former is of the same size as that of the latter, no matter what the A_1A_1 decay pattern may be. Therefore, we conclude that our results are encouraging in an attempt to establish the aforementioned NMSSM no-lose theorem at the LHC.

For a general study of the NMSSM Higgs sector (without any assumption on the underly-

[3]See Refs. [14]–[16] for a complementary approach, named 'more-to-gain theorem', attempting to define regions of the NMSSM parameter space where more Higgs states are visible at the LHC than those available within the MSSM.

[4]The scope of other decays, $A_1A_1 \to jjjj$, $A_1A_1 \to jj\tau^+\tau^-$ (where j represents a light quark jet) or $A_1A_1 \to \tau^+\tau^-\tau^+\tau^-$ is very much reduced in comparison.

ing SUSY-breaking mechanism) we used here the `NMHDECAY` code (version 1.1) [21]. (We have verified that the pattern described below does not change if one adopts the newest version [22].) This program computes the masses, couplings and decay Branching Ratios (BRs) of all NMSSM Higgs bosons in terms of the model parameters taken at the EW scale. The computation of the spectrum includes leading two-loop terms, EW corrections and propagator corrections. `NMHDECAY` also takes into account theoretical as well as experimental constraints from negative Higgs searches at collider experiments. For our purpose, instead of postulating unification, we fixed the soft SUSY breaking terms to a very high value, so that they have little or no contribution to the outputs of the parameter scans. Consequently, we are left with six free parameters: the usual tanβ, the Yukawa couplings λ and κ, the soft trilinear terms A_λ and A_κ plus $\mu_{\rm eff} = \lambda\langle S\rangle$.

We have used `NMHDECAY` to scan over the NMSSM parameter space defined in [16] (borrowed from [23]), with the aforementioned six parameters taken in the following intervals[5]:

$$\lambda:\ 0.0001 - 0.75, \quad \kappa:\ -0.65 - +0.65, \quad \tan\beta:\ 1.6 - 54,$$
$$\mu,\ A_\lambda,\ A_\kappa:\ -1000 - +1000\ \text{GeV}.$$

Remaining soft terms which are fixed in the scan include:
- $m_{Q_3} = m_{U_3} = m_{D_3} = m_{L_3} = m_{E_3} = 2$ TeV,
- $A_{U_3} = A_{D_3} = A_{E_3} = 1.5$ TeV,
- $m_Q = m_U = m_D = m_L = m_E = 2$ TeV,
- $M_1 = M_2 = M_3 = 3$ TeV.

The allowed decay modes for neutral NMSSM Higgs bosons are into any SM particle, plus into any final state involving all possible combinations of two Higgs bosons (neutral and/or charged) or of one Higgs boson and a gauge vector as well as into all possible sparticles. We have performed our scan over several millions of randomly selected points in the specified parameter space. The data points surviving all constraints are then used to determine the cross sections for NMSSM Higgs hadro-production. As the SUSY mass scales have been set well above the EW one, the production modes exploitable in simulations at the LHC are the usual ones, the so-called 'direct' Higgs production modes of [25].

As we are aiming at comparing the yield of VBF ($qq \to qqH$) against HS off W bosons (W-HS) ($qq \to WH$) and off $t\bar{t}$ pairs (tt-HS) ($gg \to ttH$), it is of relevance to study in Fig. 1 the light Higgs, H, hadro-production cross sections at the LHC in the SM, as the NMSSM rates would be obtained from these (for a given Higgs mass) by rescaling the VVH and ttH couplings. We see that in the SM W-HS dominates for Higgs masses below 80 GeV while VBF becomes the leading channel above such a value (in the NMSSM these two processes are rescaled by the same amount). The case tt-HS is generally subleading (even in presence of appropriate NMSSM couplings), but not negligible at low Higgs masses. Besides, as intimated earlier, notice that HS off Z boson is always very small, so we will ignore it in the remainder of the paper. It is also worth recalling that gluon-gluon fusion ($gg \to H$), despite

[5]Notice that a top quark pole mass of $m_t = 175$ GeV was used as default, though we have verified that values within current error bands (see [24]) have a numerically small impact on our analysis, thus leaving the main conclusions of the paper unchanged.

being the mode with largest production rates, plays no role in our case, as $H_{1,2} \to A_1 A_1$ decay channels would not be extractable in this case from the background. (Notice in the figure the normalisation via NLO QCD throughout.)

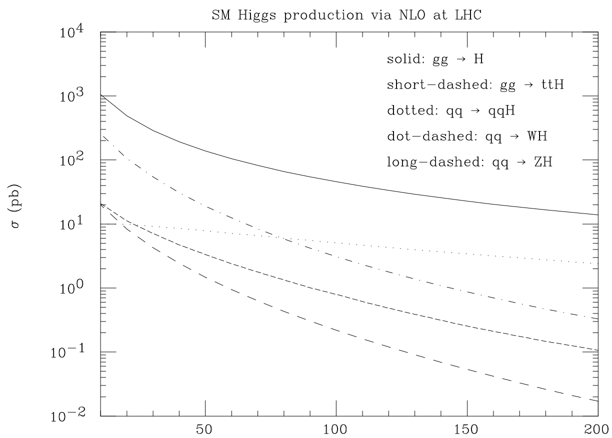

Figure 1: The Higgs production cross sections through NLO QCD in the SM at the LHC.

As a second step we computed the NMSSM total cross section times BR into $A_1 A_1$ pairs for VBF and W-HS + tt-HS for each of the two lightest neutral Higgs bosons, H_1 and H_2. We display these rates in Fig. 2 as a function of M_{H_1} and M_{H_2}. Here, one can appreciate that there exist more possibilities of establishing a H_1 signal than one due to H_2. Whereas the potential to detect the heavier of these two Higgs states is confined to masses above 115 GeV or so and probably below 140 GeV, where VBF is largely dominant with respect to W-HS + tt-HS, in the case of the light state there exists a low mass window where production rates via the latter two processes combined are comparable to those from the former, most often within 10–20% from each other. In fact, at times, W-HS + tt-HS rates are larger than those for VBF, the more so the lower the H_1 mass. (Recall that all parameter points examined here are compliant with collider bounds, even those at very low Higgs mass, as these correspond to reduced Higgs couplings to gauge bosons.) Now, one should bear in mind that the rates in Fig. 2 do not include yet the efficiency to trigger on the signal. In the case of VBF, one triggers on one forward and one backward jet, with $p_T > 20$ GeV, $|\eta| < 5$ and $\eta(\text{fwd}) \cdot \eta(\text{bwd}) < 0$. The efficiency is here about 60%. In the case of W-HS, one triggers on a high transverse momentum lepton (electron or muon), with $p_T > 20$ GeV and $|\eta| < 2.5$. In this case the efficiency is lower, about 19%, primarily due to the fact that a W boson decays into electron/muons only about 20% of the times. The efficiency for tt-HS is 14%, as one top is required to decay hadronically and the other leptonically. (Note that the efficiency values quoted are basically independent of the Higgs mass.) Even so, the W-HS component, aided by the tt-HS one, would make a sizable addition to the production rates of VBF. As we expect the efficiency of extracting whichever $H_{1,2} \to A_1 A_1$ decays to be the same in both processes[6], we see a potential in improving the signal yield by using all mentioned channels,

[6]If anything, since no actual b-tagging was enforced in the analyses of Refs. [13, 19], whenever $A_1 A_1$ hadronic decays are present, we would expect the efficiency to worsen for the case of VBF, because of jet combinatorics.

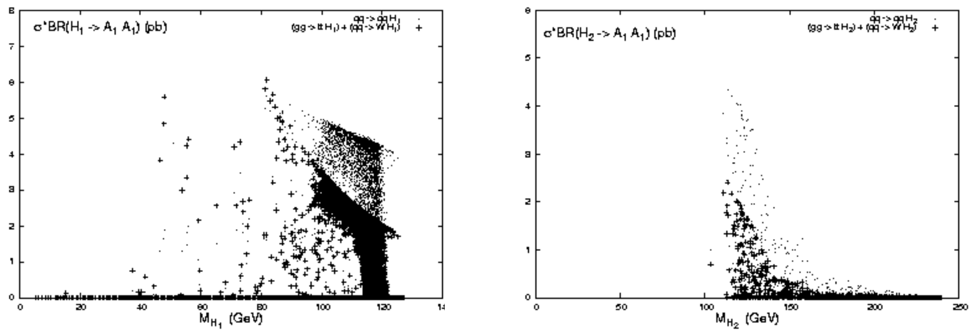

Figure 2: Cross section times BR of H_1 (left) and H_2 (right) plotted against their respective masses. The symbol '$\cdot$' refers to VBF while '+' to W-HS + tt-HS.

beyond what achieved by using VBF alone.

By recalling that the efficiency to trigger on VBF is at least three times the one to isolate W-HS + tt-HS, it is of particular interest to estimate the proportion of points where the latter gives more cross section than the former. Despite we found that W-HS + tt-HS very rarely exceeds VBF by more than a factor of three, there are clear zones of NMSSM parameters space where W-HS + tt-HS is consistently larger than VBF, those producing M_{H_1} values below 80 GeV, indeed the SM crossing point seen in Fig. 1. Evidently, this mass range is of relevance to $H_1 \to A_1A_1$ decays only, see Fig. 2. In fact, for the case of $H_2 \to A_1A_1$, cross sections are much smaller in comparison and VBF is always very dominant, as – for potentially detectable rates – M_{H_2} is above ≈ 115 GeV and below ≈ 140 GeV. Finally, notice that $H_2 \to H_1H_1$ decays very often compete with $H_2 \to A_1A_1$ [23]. In fact the former occur almost as often as the latter over the NMSSM parameter space investigated here. To make use of this channel too, a slight modification of the procedures advocated in [13] would be required.

Even after accounting for the trigger efficiencies, the VBF cross sections plotted in Fig. 2 are in the same range as those probed in [13][7], so that, for similar M_{H_1} and M_{H_2} masses, we would expect to obtain the same overall detection efficiencies seen back then also for all our points falling in the mass range, say, 50 to 120 GeV. Crucially, NMSSM parameter points giving the highest cross sections for VBF are the same yielding the largest rates for W-HS + tt-HS. More in general, from Figs. 3a–b, one can also gather where the regions of highest cross sections, for both channels (VBF and W-HS + tt-HS) and Higgs flavours (H_1 and H_2), lie in the NMSSM parameter space. In particular, their distribution is quite homogeneous as they are not located in some specific areas (i.e., in a sense, not 'fine-tuned'). Altogether, the proportion of parameter space where the two production modes yield potentially detectable Higgs signals (at least according to the analysis in [13]), say, above 1–2 pb (prior to including tagging efficiencies and A_1 decay rates), is 0.21% for VBF and 0.13% for W-HS + tt-HS. However, if production cross sections of 4 pb or upwards are required to render the $H_1 \to A_1A_1$ signal visible, then the rates reduce to 0.096% and 0.0019%, respectively. For the case of $H_2 \to A_1A_1$, the numbers are typically 20 and 10 times smaller, for the case of VBF and

[7]We have in fact been able to reproduce most of the points discussed therein.

W-HS + tt-HS, respectively.

Clearly, while the production cross sections (after triggering), the selection procedures and efficiencies to extract the Higgs decays may well be the same in both samples, the background will differ. In fact, whilst in the case of VBF the latter is dominated by top-antitop pair production and decay for V-HS and tt-HS we expect that (more manageable) $WZ+$ jets events will be the largest noise, assuming the most promising Higgs signature discussed above (i.e., $b\bar{b}\tau^+\tau^-$). A detailed phenomenological study, based upon parton shower, hadronisation and detector simulation (like in Refs. [13, 19]), is obviously in order before drawing any firm conclusions from our very preliminary study. (In this respect, it is also interesting to see how the mass of the decaying Higgs bosons, H_1 and H_2, relates to that of the light A_1 state: this is illustrated in Fig. 4.) Nonetheless, we thought it worthwhile to alert the LHC experiments to the possibility of supplementing the search for $H_{1,2} \to A_1 A_1$ signals via VBF with that through W-HS + tt-HS, as such Higgs decays are relevant in a region of NMSSM parameter space where the two production modes are competitive. Whilst the efficiency of tagging two forward/backward jets in VBF is three times higher than that to trigger on a high transverse momentum electron/muon in W-HS + tt-HS (mainly in virtue of the leptonic BR suppression in the second case), the combination of the latter two remains competitive with the former over the Higgs mass range relevant to these decays, 50 to 120 GeV or so, the more so the lighter the mass of the decaying Higgs state. (Notice that such a low mass scenario is one alleviating the so-called 'little fine-tuning problem' of the MSSM, resulting in LEP failing to detect a light CP-even Higgs boson, predicted over most of the MSSM parameter space, as in the NMSSM the mixing among more numerous CP-even or CP-odd Higgs fields enables light mass states being produced at LEP yet they can remain undetected because of their reduced couplings to Z bosons.) Thus, the chances of establishing a no-lose theorem in the NMSSM at the LHC via the aforementioned Higgs-to-Higgs decay mode might improve considerably if the Higgs state strongly coupled to gauge bosons is the lightest one. Our analysis was based on a fairly extensive scan of the NMSSM parameter space incorporating the latest experimental constraints. Detailed MC event generation studies will be available soon.

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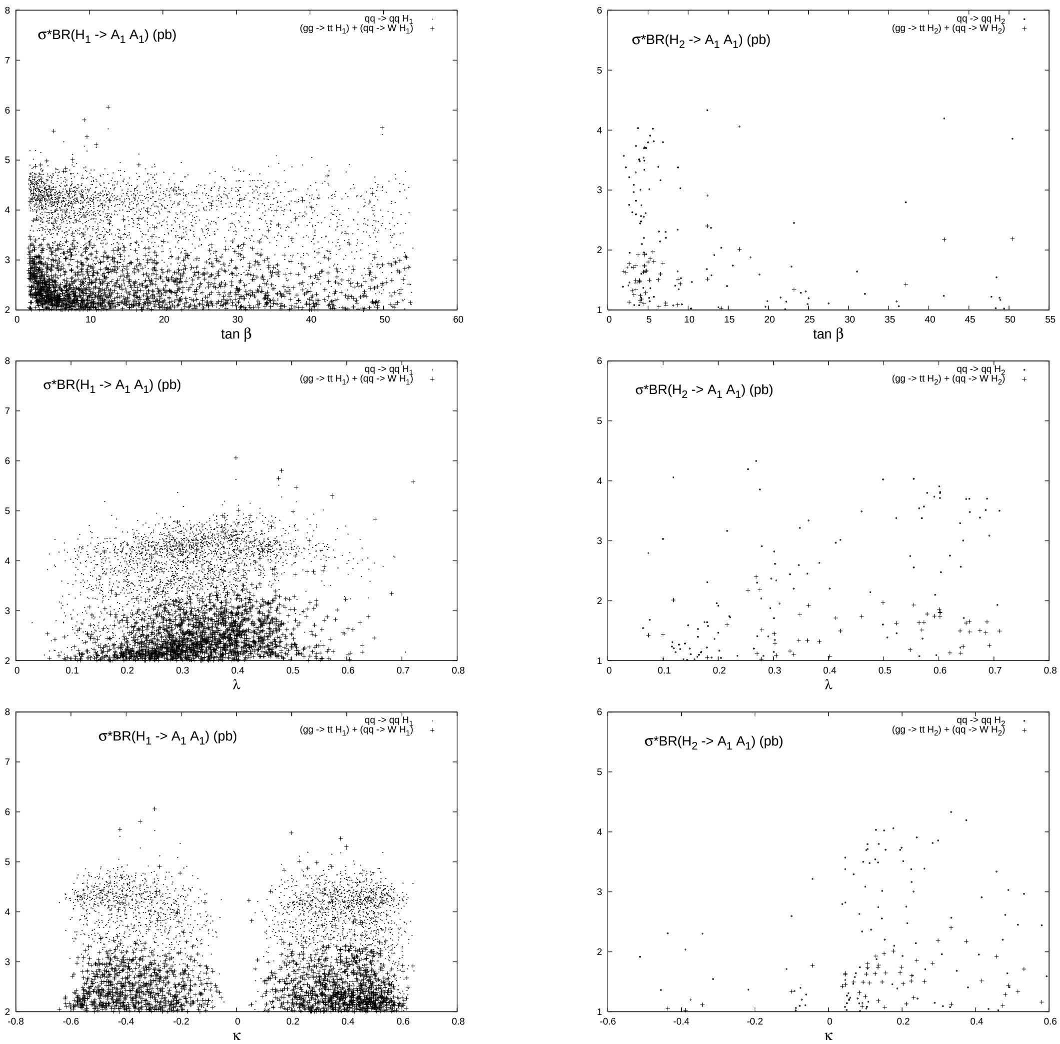
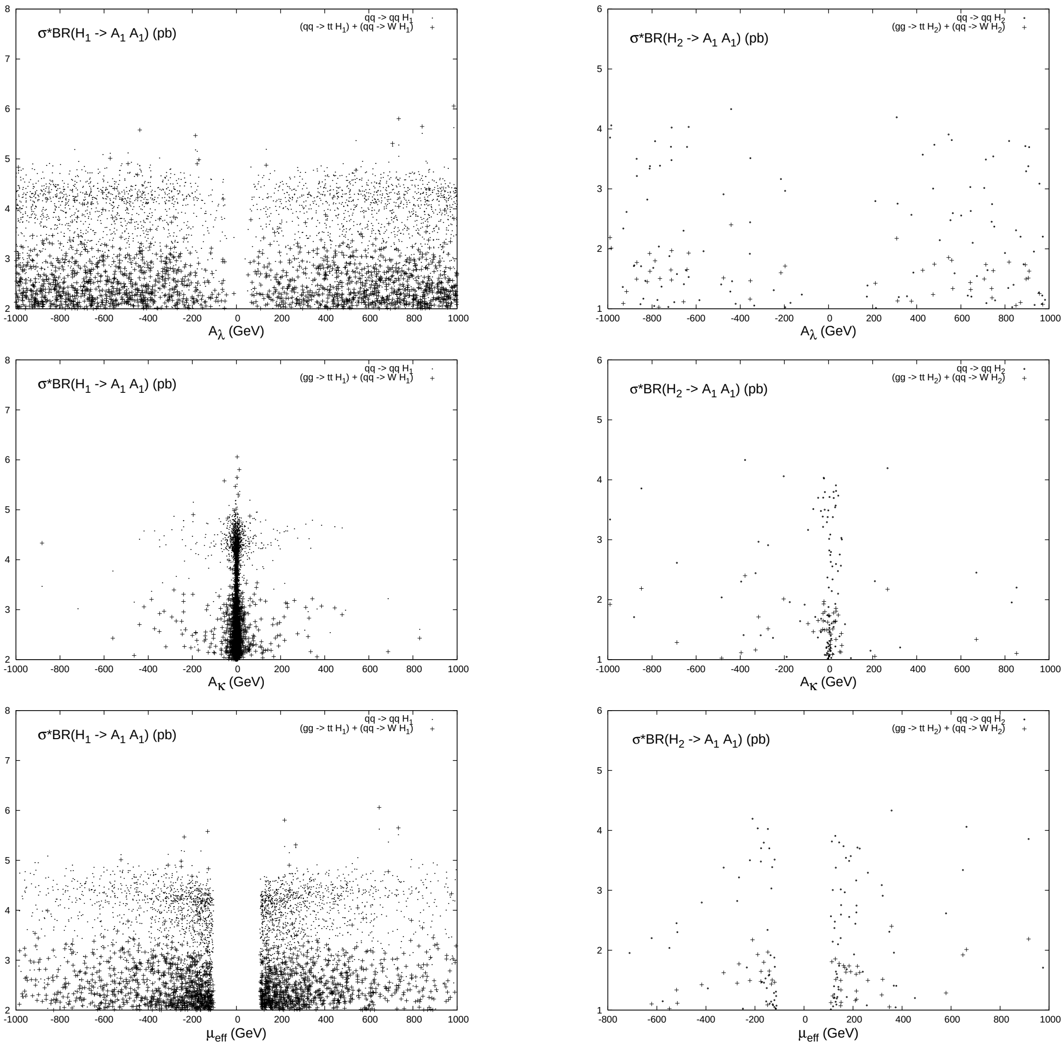

σ*BR(H1 -> A1 A1) (pb)
qq -> qq H1
(gg -> tt H1) + (qq -> W H1)
tan β
σ*BR(H2 -> A1 A1) (pb)
qq -> qq H2
(gg -> tt H2) + (qq -> W H2)
tan β
σ*BR(H1 -> A1 A1) (pb)
qq -> qq H1
(gg -> tt H1) + (qq -> W H1)
λ
σ*BR(H2 -> A1 A1) (pb)
qq -> qq H2
(gg -> tt H2) + (qq -> W H2)
λ
σ*BR(H1 -> A1 A1) (pb)
qq -> qq H1
(gg -> tt H1) + (qq -> W H1)
κ
σ*BR(H2 -> A1 A1) (pb)
qq -> qq H2
(gg -> tt H2) + (qq -> W H2)
κ

(a)



(b)

Figure 3: Cross section times BR of H_1 (left) and H_2 (right) when potentially visible, i.e., limited to those NMSSM parameter points for which both cross sections times BRs are larger than 2(1) pb for $H_1(H_2)$, plotted against the following parameters: (a) $\tan\beta$, λ, κ; (b) A_λ, A_κ and $\mu_{\rm eff}$.

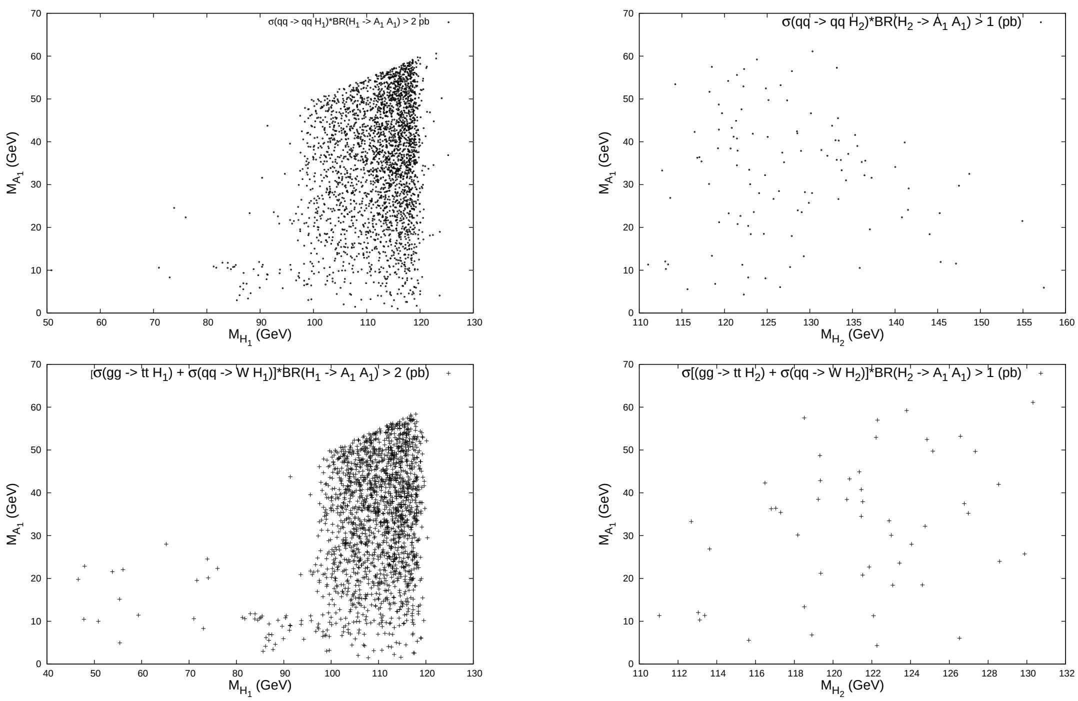


Figure 4: Distribution of the H_1 (left) and H_2 (right) masses with respect to that of A_1, when VBF (top) and W-HS + tt-HS (bottom) are potentially visible, i.e., limited to those NMSSM parameter points for which both cross sections times BRs are larger than 2(1) pb for $H_1(H_2)$.